Reply to LHCC Questions in Regards the CMS HCAL TDR

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1. Energy Resolution:

In general, the design aim was to achieve a stochastic coefficient of 100% and a constant term of 5%. The combined system achieves this goal (Fig. 1.25 of the HCAL TDR), while the stand alone resolution is somewhat better (Fig. 1.25 also). We have verified that this energy resolution does not degrade the physics processes. One could build a better calorimeter but it would not improve the physics performance of CMS. For example, the process H → WW → J+J+l+ν was studied. Very simple estimates of the rms error of the dijet mass, dM, due to jet energy resolution, dE, lead to:

$$dM/M = (dE/E)/\sqrt{2} \qquad (1)$$

Since the fixed cone jet finding algorithm has errors due to clustering, pileup, and out of cone radiation which are at the level of dM/M from 6% to 10% [1], [2], depending on dijet boost, we impose the condition that dE not degrade this resolution. The baseline defined in the TDR fulfills this condition, since the jet EM energy is well measured and since the jet energy error is less than the error on any of its components [2].

A baseline process that has been studied is H → bb for a Higgs mass of 85 GeV. Two cases were studied, with HCAL stochastic coefficient 85% and 120% and constant term 6% and 10% respectively. These values span the baseline CMS HCAL performance as specified in the HCAL TDR. No effect due to resolution was seen, as shown in Fig. 1. The quality factor, $S/\sqrt{B}$, is the same within statistics. Another study at 100 GeV Higgs mass lead to the same conclusion. Note that pileup from 1 crossing is included in these studies, which tends to soften any resolution effects since the background energy within the jet cone rises.

The missing energy resolution is also not adversely effected by the measured HCAL performance, as shown in Fig. 1.14 of the HCAL TDR.

2. Angular Resolution:

The angular resolution was chosen so as not to degrade the dijet mass resolution in the extreme (worst) case of boosted W from a heavy Higgs (Pt ~ 0.5 TeV for the W, mass ~ 1 TeV for the Higgs). The results are shown in Fig. 2, which indicates that for towers with transverse segmentation better than $\Delta\eta = \Delta\varphi < 0.1$ there is no degradation. One could do better, but there is no physics, which requires better angular resolution.

In fact, ultimately the lateral extent of a hadronic shower defines an irreducible minimum tower size. In CMS, the HCAL towers of HE near $|\eta| = 3$ have segmentation = 0.174, reflecting this fact. The HF geographic sector is a factor ~ 2 further away from the interaction point. Therefore, we can use 0.087 segmentation again, especially since the HF quartz technology is only sensitive to the electromagnetic core of a hadronic shower. Nevertheless, at $|\eta| \sim 5$, the effective single hadron shower size is ~ the size of a jet of “cone radius” R = 0.5.

A simple calculation, for symmetric decays, is that the boosted W has a mass error dM due to angular width of the tower = $\Delta\eta$.

$$dM/M \sim \Delta\eta(M_H/M_W)/4\sqrt{6} \qquad (2)$$

Using Eq.2 makes the behavior seen in Fig. 2 plausible. Only the large mass Higgs gives a noticeable contribution to dM, and that only for $\Delta\eta >$ 0.1. For smaller tower sizes “intrinsic” detector independent effects dominate the mass resolution.

A summary of detector dependent effects is given in Fig. 3. The two plots show the mass resolution for low Pt Z and for low Pt Z’ of 1 TeV mass. The labels a - g refer to: a = cone R =0.7, b = a + the underlying event, c = b + different HCAL resolutions up to 70% stochastic + 4% constant, g = d + e/h = 1.3 (effective e/h). Clearly, the 25 overlapping events of LHC operation at full luminosity will further soften the detector dependent effects. In any case, we see no serious degradation of performance due to detector dependent effects.

An additional study [3] of boosted W, showed that, for the baseline tower size the cm decay angular distribution W $\rightarrow$ JJ can be used as a significant cut in the search for heavy H. The results for W + J backgrounds are shown in Fig. 4 for parton level and 3 possible tower sizes. Clearly, the TDR baseline tower size is sufficiently small. In this study all hits in a cone R = 0.7 were taken to be the W, while the 2 jets were found within this large cone.

3. Intercalibration of the CMS Calorimetry:

There are ECAL, H1, H2, and HO longitudinal compartments. The individual HCAL towers are first calibrated using the radioactive source. It was shown in SDC [1], that the source tracks a muon calibration good to 2%. Therefore, the radioactive source allows an HCAL tower to tower and compartment to compartment calibration good to better than 2% on the mean energy. Note that this is less than the constant term, so that calibration will not degrade the calorimeter energy error even as the calorimeter itself will not limit the physics performance of CMS.

The ECAL will be calibrated in a test beam. After installation, $Z \rightarrow ee$ decays will be used to maintain the resolution. Note that ECAL is not a sampling device, and thus shows no magnetic field effects. The HCAL will be calibrated using a few towers in a test beam, and transferring that calibration to other towers and compartments using the radioactive source. The HCAL H1, H2 and HO compartments thus have an initial calibration set by the radioactive source with a beam calibration carried over from a few modules placed in a test beam and exposed to a variety of energies of beams of electrons and pions.

In addition muons in the beam provide a crosscheck of the source measurement. We also will construct a cosmic ray test stand, which will be housed in the HCAL assembly area, building 168. A prototype for this device was already built for SDC and will be used at Fermilab to establish the cross calibration of the source and cosmic ray muons. This device will be used to establish the tower response of the assembled wedges in comparison to the source, which was used to track each and every tile during the manufacturing QC phase.

The procedure outlined on pg. 429 of the HCAL TDR will be used to transfer the calibration from test beams to jets and from HB/HE to HF. Note that in the test beam H2 we were able to intercalibrate each layer of the HCAL with only 1-1.5 p.e./mip (see Fig. 1.21 of the HCAL TDR).

Therefore, we have confidence that an absolute calibration of each tile good to 2% will be initially available and will be tied to test beam and cosmic ray muon data.

4. Monitoring of the Calibration:

The H1 compartment can be calibrated with unity weight by appealing to "continuity" in hadronic showers, as shown in Fig. 5. As stated in the TDR, we will overweight the H1 contribution to the calorimeter sum in order to correct for the large e/h ratio of ECAL, as discussed later.

The relative weight of the H1 compartment has a fairly shallow minimum, as seen in Fig. 6a. Hence, the source is again sufficient to set the initial calibration.

The function of the H1 compartment is not to establish the hadronic shower development per se, but rather to sample how much of the jet has deposited its energy in ECAL and thence raise the response to correct for the large e/h response of the crystal ECAL. We have studied the optimal depth of H1 and chosen to have a single sample as close to the back of ECAL as possible. The study using H2 test beam data for an H1 compartment of 1 and 3 layers on HCAL (3 cm/layer) is shown in Fig. 6a and Fig. 6b. The linearity is restored in both cases. In the case of a single layer, the H1 response must be increased by a factor 4.5 with respect to a muon calibration of that layer, indicating that H1 is used to increase the low ECAL pion response.

The energy resolution using a constant weight for H1 is shown in Fig. 6b. Clearly, the single layer of H1 is superior to the 3-layer case. The minimum resolution for 300 GeV pions goes from 10%, muon weighted, to 8.5%, optimally weighted. Note that the minimum is 9.3% in the 3-layer case. Note also that the best weight is near to that which restores linearity, as might be expected. Clearly, using more HCAL depth segments washes out the information from ECAL contained in H1, and, as the memory of ECAL is lost, the ability to correct for the large ECAL e/h ratio is lost.

The HO layer will have an initial calibration set by the sources. In situ, "continuity" between the calorimetry inside the magnet and that outside will be sufficient to maintain the calibration. The relationship is shown in Fig. 7 for 300 GeV pions. Clearly, the required degree of accuracy is not very stringent.

Clearly, the initial calibration can be continuously monitored in situ by appeal to hadron shower "continuity". In addition, as the radioactive source deposits a fixed absolutely normalized amount of energy into the tiles, a cross check exists for all tiles during the annual long shut down and access. We will also have muons, which give absolute calibration of each compartment in situ during data taking. The CDF endplug calorimeter, using similar techniques, achieved a 2-3% absolute calibration.

5. The HPD R&D Plan:

The optics of the HPD are well understood, having been tested in a 5T magnetic field at U. of Minnesota and derived from first principles [4]. We plan to make the transit time as short as is possible, < 0.2 nsec, by asking DEP to provide devices with the minimum practical distance between photocathode and PIN diode. This choice will make CMS as magnetic field insensitive as possible.

The HPD meets specifications for CMS already in the areas of uniformity, high rate performance, linearity, crosstalk, resolution, and cost effectiveness. Most of these issues have been summarized in the TDR.

The only remaining issues are the risetime, lifetime and time to failure, response of the whole readout chain to radiation, and practical issues, such as tolerances and alignment in a magnetic field.

The risetime is determined by the drift time of the holes, which are collected on the side opposite the illumination. This type of "backside" illumination, or "T-type" diode is a n+ substrate with a thin n++ entrance layer and p+ implantation regions on the opposite side, which create the individual pixels [5]. Thus, the electron-hole pairs are formed in a low field region near the n++ layer, the electrons move toward the n++ layer and the holes toward the p+ pixels. The availability of substrate material and ease of p+ implantation determined this structure; however, Canberra is experimenting with other structures that will allow n-type pixels in a p-type substrate. The risetime will then be determined by the electron mobility instead.

This solution is premature for our next round of tubes, which are already under preparation. Since the drift time of the holes depends on the thickness of the diode (53 nsec for the 300 micron thick wafers at depletion)[5], DEP will be making a set of the tubes with thinner (200 micron) silicon. Since Canberra feels that the yield may be worse after handling, thus pushing the cost per tube up, they will also make a set of tubes with the standard thickness. An effort will be made to form junctions, which can operate at much higher bias voltages, thus operating in overdepleted mode. The expected risetime should then be <10 nsec for both cases, which should not degrade the intrinsic tile/WFS effective deflourescence time. [6]

Time to failure and lifetime are hard to quantify when there are very few devices available for testing. Lifetime tests are continuing on a tube at DEP under constant illumination. In addition, the University of Minnesota has just received a second 61-channel tube similar to the CMS design, which is being put into a lifetime testing station for a year's worth of accelerated lifetime testing. Lifetime is expected to be better in the bump-bonded tubes as they do not have the outgassing from holes and ceramic epoxy used in wire-bonded tubes

The HPD has been tested at the Oak Ridge National Laboratory using a Californium source, which was moderated to approximate the predicted neutron spectrum at the location of the tube. The behavior was completely consistent with a simple monotonic increase in leakage current from the internal silicon diode. The gain and current fluctuations remained the same, despite the increase. We plan to repeat these tests with the actual CMS design HPD as well as the entire electronics chain, including QIE, ADC, and optical driver. Since the last test compressed 1000 years of LHC running into a few weeks, we plan to decrease the dosage and monitor the response in situ at more frequent time intervals.

6. HPD Alignment in the B Field:

The trajectory of the photoelectrons in the HPD follows the B field in a tight helix. The passive layer between pixels is ~ 400 μm, while the gap between cathode and PIN diode is ~ 1.5 mm. Therefore, we need to align the B and E fields to ~ 5 degrees to avoid image cross talk.

The CMS field is shown in Fig. 8 as taken from the Magnet TDR. The HPD are located at a radius ~ 2 m and at z ~ 4.3 and 5.5 m respectively for HB and HE as given in Fig. 1.2 of the HCAL TDR. The field there is quite axial, as we will confirm in a field map planned to be done prior to installation of HB and HE into the magnet. Therefore, we will align the HPD axially, with small adjustments for optimal alignment.

The alignment scale is several degrees with respect to the local field direction. We anticipate that no problems with the alignment will be encountered.

7. Timing Capabilities of HCAL:

<u>HB and HE</u>

The timing characteristics of the tile-fiber structures were described in Section 9.2.1 of the CMS HCAL TDR. The shape of the light pulse in one layer is an initial step followed by an exponential decay corresponding to the fluorescence characteristics of the combined scintillator - waveshifter system. Measurements on the materials selected for HB and HE give the time constant as ~ 12 nsec using a single exponential approximation. The test results are shown in Fig. 9 where the fit to a single exponential yields 8.2 nsec for an SDC tile/WLS [6]. The signal is 90% contained in ~ 1 LHC crossing. This waveform is only realized a high light levels. For low energy showers, Poisson fluctuations can considerably distort the shape.

The final waveform arises from convoluting the light emission shape with the impulse response of the HPD and summing over the various layers, each with a slightly different arrival time. Our present estimate is that, on average, 68% of the signal occurs in the event crossing itself, 29% occurs in the subsequent 25 nsec interval, and 3% occurs in the interval following that.

The readout of a tower is done as a waveform digitizer; the amount of charge in each 25 nsec interval is digitized and stored in a pipeline memory. For each accepted event, five consecutive samples are readout: two before the crossing of interest to obtain the baseline level and two after the crossing of interest to obtain the true energy. A fit is done to the five samples to extract the energy deposited in the tower corrected for baseline shifts and time of arrival. In the case of pile-up, such as another hit in that tower in either of the two crossings following the one of interest, a cruder extraction algorithm is used producing an energy value with a larger uncertainty.

Resolution on the arrival time of a signal is affected by pileup and depends strongly on the size of the signal. For high light levels, 100 photoelectrons or more, and in the absence of pileup, the resolution is easily at the 1 nsec level as it depends only on the relative heights of the signals in the three bins. For low light levels, the resolution degrades, as Poisson statistics on the emission of photons becomes significant. For example, 10 photoelectrons become 6.8, 2.9, and 0.3 in the three bins on average. The fluctuation of just one photoelectron from the first bin into the second bin would pull the fitted time later by about 3 nsec. Nevertheless, at the 10 p.e. level, HCAL will provide muon timing to a single LHC bunch from HOB and HOE.

Similar scintillator calorimeters, e.g. CDF, with comparable light yields, e.g. 20 p.e./mip, have achieved 2-3 nsec timing resolution. Our intent is to measure this carefully with our first preproduction prototype in the H2 test beam in 1998, where we will have HPD close to the final product.

HF

The light pulse produced is due to Cerenkov radiation from relativistic shower particles and, as such, is very fast. A very fast photomultiplier tube has been selected for the readout that can easily produce pulses shorter than 10 nsec (Figure 8.16, HCAL TDR). Therefore all of the light produced by a given event is collected in that crossing interval; there is no pileup from previous or subsequent crossings.

The results of our available timing measurements are summarized on page 64 of the HCAL TDR ("HF signal timing measurements"). From Fig. 1.41 b) it can be deduced that the signal collection is completed in less than 10 nsec using a relatively slow XP2020 PMT. We have used XP2020 PMTs for all our calorimetric measurements. Also from the same figure (that shows arrival times for the same type of signal) one can deduce that the time resolution (the half width of the distribution of the arrival times -the peak maxima-) will most likely to be better than 1 nsec. This estimate agrees with the fact that we can separate, in Fig. 1.41 a), two different arrival times of the same signal (primary and the reflected).

8. HF Quartz Fiber Procurement:

Fiber procurement will be not an issue; many thousands of kilometers of quartz core fibers can be manufactured in a timely fashion. The cost of quartz fibers comprises the large fraction of the detector cost and here we spend effort to reduce the cost as much as possible.

The quartz fibers that we used in our prototypes were produced either by Polymicro Inc (USA) or INFOS (Russia). Polymicro has produced both synthetic quartz core fibers with either fluorine doped silica cladding (QQ) or polymer cladding (QP). INFOS are capable of producing QQ type fibers. For the quantities that are needed for the HF, Polymicro has provided an official quote of 1.41 $/m for QQ and 0.21 $/m for QP.

The cost of QQ fibers it is mainly driven by the cladding. We thus, so far, have used fibers such that the clad to core ratio, a common measure of cladding thickness for a given fiber, is 1.05. Further reduction in this ratio appears possible (1.02) and this would save about 40% of fiber cost (Dr. G. Nelson of Polymicro), if these types of fibers perform satisfactorily. We are presently in contact with a firm in Turkey (HESFIBEL) and exploring the possibility of producing considerably less expensive fibers than that are offered by Polymicro. We are pursuing this alternative aggressively.

Note that the total HF cost estimate in the HCAL TDR is made based on the prices quoted above by Polymicro. Our plans call for optimization of the border, in view of the performance and cost, between QQ and QP fibers in the detector.

9. HF Magnetic Shielding:

The magnetic field at the PMT location for HF is ~ 150 G. This level of stray field does not require heroic measures. We plan to use a soft iron box to house the PMT and to surround each PMT with a coaxial soft iron cylinder and inside that a "mu-metal" magnetic shield. This technique has been the standard for some time. A schematic of the HF PMT box is shown in Fig.10, showing the PMT and magnetic shielding locations.

The field map indicates that the field direction is roughly 70% along z. A typical PMT will operate at >80% of nominal gain at <0.1mT along its axis, which in the case of HF is along z. An inner radius of 1.5 cm for the PMT primary shield, a 6 mm thick soft iron/mild steel can reduces a 150 mT field by at least a factor of 100, to 1.5 mT. A mu metal shield of 2 mm thickness conservatively reduces a field of 1.5 mT by nearly 3 orders of magnitude.The iron and mu-metal extend from the PMT box through the shield ring for about 30 cm, or over 10 inner diameters. These conditions will easily allow operation at >99% of zero field gain.

10. HF Location:

The HF location was chosen so as to reduce the radiation burden on the CMS tracker, on the forward muon system and on HF itself. If HF were nearer the interaction point, the rates in the tracker would increase. In addition, the location of HF allows the forward muon system to be very well shielded from the CMS calorimetry.

Finally, the radiation burden on HF is reduced a factor ~ 4 simply by moving it a factor 2 further away from the source than the HE location. In addition, this factor also helps in jet pattern recognition, as the jets have a factor 2 larger spatial extent in HF. Note that, even with this factor, and with the quartz fiber technique reducing the effective detected lateral extent of hadrons, the effective size of a hadron shower is ~ the size of a jet at $|\eta| \sim 5$. The decision of CMS was to locate HF so as not to compromise the tagging jet pattern recognition capabilities of HF.

The use of tagging jets may well turn out to be crucial if WW scattering at high mass is the manifestation of electroweak symmetry breaking via strong VV interactions.

The CMS Collaboration discussed at length the position of the HF at several Collaboration Meetings in 1994. The decision was reached to locate the HF outside the main body of the CMS detectors.

Three locations were discussed:

1) As an extension of the endcap (HE)
2) Attached to the ME support (front face at z about 900 cm, back face at about 10.65 m)
3) At the present location, at z about 11 m, the closest to the outer face of CMS.

Position 1) was immediately discarded because of the enormous background induced in the forward/backward parts of ECAL and Tracker.

Position 2) has the following inconveniences:

a) For $|\eta| = 5$, the inner radius of the HF should be 10 cm, leaving no room for the beam pipe.

b) The lateral leakage by the outer surfaces will induce noise in the muon chambers (ME/2, 3 and 4) mainly due to a large flux back of neutrons.

c) The induced activity is more than twice larger than at z = 11 m.

It was considered too dangerous to have the HF present when CMS opens the endcaps. The solutions with removable HF in that position were considered too complicated for practical reasons.

Position 3) is the nearest possible to the CMS exit compatible with an extra shielding to minimize the noise at ME/4. In this position, it is relatively simple to remove HF when the inner CMS systems need to be opened up.

In addition:

a) The maximum radiation dose absorbed in the HF quartz fibers gets minimized (is proportional 1/Z**2)

b) The transversal size of HF response to hadronic jets will be basically dominated by the jet size rather than the hadronic shower size. This in turn will allow to keep fiducial volume as close to the physical volume of the HF as possible, and to minimize the impact of the pile-up noise fluctuation for tagging jet detection.

11. HE/HF Interface:

The response to jets is given in Fig. 1.56 of the HCAL TDR, while the single particle response is given in Fig. 1.55 [7]. The $|\eta| = 3$ boundary has been studied, and the CMS calorimetry is quite homogeneous across the HB/HE boundary and the HE/HF boundary. Note that tile/WLS calorimetry allows us to have the active sampling layers extend essentially all the way to the calorimeter boundary. We have exploited this feature of the CMS technology choice in order to pull the HF back and thus achieve better jet measurements and reduced dose in HF.

We have performed full GEANT simulations of the CMS boundary at HE/HF for tagging jets. Roughly half of these jets appear in HE, the other half in HF. There is a slight loss of energy from jets that strike HE and initiate the showering of individual hadrons there. In the magnetic field, some jet energy is swept away from striking HF. As shown in the TDR, this effect is not dramatic. It does not significantly degrade the tag jet pattern recognition nor the tag jet E_{tJ} measurement. We have also looked at missing Et in dijet events generated by mismeasures of jets in the HE/HF region. The spectrum shown in chapter 1 of the TDR indicates that real backgrounds from ν dominate at even moderate values of missing Et.

Finally, we are evaluating whether lining the $|\eta| = 3$ cone of steel in the forward muon system with scintillators is cost effective in reducing the losses at the HE/HF interface even further. If such scintillators appear to be effective they can easily be added.

As soon as the CMS ECAL design in this region is completed and the appropriate ECAL geometry implemented into the CMS GEANT data base, we plan to repeat a detailed simulation of HE/HF transition region. We will concentrate mainly on the study of the possible tails of the calorimeter response. In addition, a combined test beam run with the ECAL, HE and HF modules, to measure experimentally the HE/HF interface region, will be carried out in the summer of 1998.

12. HB Depth inside the Solenoid:

The decision on the depth inside the coil can only be taken when the size of the CMS tracker and ECAL are finalized. In particular, the space requirements of the ECAL electronics are not yet perfectly well known. As the TDRs for the end of 1997 will complete both ECAL and Tracking, the decision is imminent. A quantitative comparison of the performance of the calorimetry is provided in Fig. 1.22 and Fig. 1.23 of the HCAL TDR. The difference in the tails in the two cases is not overwhelming; one simply must wait longer to make the discovery of SUSY.

13. HB Sampling Gap:

Our FEA implies that the maximum deformation in a slot is a 0.4mm decrease of the gap. The gap is nominally 9.5mm +- 0.2mm, or 9.3mm minimum. The scintillator package is 7.63mm nominal, +- 0.62mm for a maximum thickness of 8.25mm. The deformed absolute minimum gap is 9.3mm - 0.4mm = 8.9mm. So even if all tolerances go in the worst direction for this gap, there will still be 0.65mm of clearance. As noted elsewhere, we have designed a series of elastic clips that will always define the scintillator package to be pressed against the rear of the absorber slot. The scale for deformations with respect to performance is 4% shift per mm of distance to the rear of the slot. The nominal gap is 0.9 mm, and the worst case of 0.4 mm less implies a worst case shift of 1.6% in the energy scale of that layer. This is less than the “constant term” of 5% which is our design goal, and a single layer does not define the tower energy scale.

14. B Field Effect in HB:

The basic effect is not unexpected [8]. We measured the “brightening” of the scintillator per se, and showed that it saturated at a value ~ (6-7) % for fields above ~ 2 T. This effect is well tracked by the muon component of the H2 test beam and by our radioactive source calibration method. We show a figure from the N.I.M. paper in Fig. 11. The data shown contains tiles alone and tiles illuminated by e beams. At B = 3T the e beam illuminated data show more effect than the source illuminated tile data.

The data from DESY using a 6 GeV e beam, and the CMS Shashlik data both clearly indicate an effect above and beyond the brightening, being some 10% at 3T. Thus, our results confirm these earlier measurements and separate the effects of increased path length in a sampling calorimeter and the effect of scintillator brightening. The effect is well reproduced in Monte Carlo models, being an electromagnetic phenomenon.

The existence of the magnetic field effect on the barrel energy response requires the use of in situ calibration [9]. We plan to calibrate barrel wedges in a test beam and to transfer the a-priori calibration to all wedges using the radioactive source. A typical in situ signal that can be used is the dijet mass from top decays with a W peak (Fig. 1.15 of the HCAL TDR).

The B field influence on the shower development of hadronic showers requires that we control the systematics of the sampling gap. As shown in the TDR, the field causes a ~ 4% energy shift, with a sensitivity of 4%/mm depending on the location of the scintillator “megatile” package in the absorber gap. We plan to insert clips to force the package to the rear of the gap. As the clearance is only ~ 1 mm total, the systematic error is < 4%/√12, or 1.15% which, when folded in quadrature with the 5% constant term is a small effect on the HCAL resolution at all energies.

Clearly, we plan to check this operation at full field using in situ physics processes. We have studied several [9], which allow us to rather rapidly make the few % corrections that are needed to correct in the HCAL barrel for the field effect.

15. Scintillator Thickness Tolerance:

The scintillator is manufactured by a casting technique on glass molds. This technique has a natural variation of about +- 10% from the sides of the casting to the middle. Specifying this variation allows the vendor to have a good yield. If we specify tighter variation, we will end up paying for the scintillator that falls outside the cuts. Based on CDF experience (where the same thickness variation was specified), we expect a +- 5% specification to increase the total cost of the scintillator by a factor of about 1.5 times.

Note that, the achieved tile to tile variation is 6.5% (see Fig. 6.34 of the HCAL TDR). For that error in manufacture, the induced constant term in the energy resolution is < 2% (see Fig. 6.6 HCAL TDR). This error is well within our stated requirements.

16. Energy Dependence of the B Field Effect:

As stated above, the effect is not new, nor is it poorly understood. Since the effect is due to the EM part of the hadronic shower, and since that fraction - Fo - increases with hadronic energy, there is an intrinsic energy dependence to the magnetic field effect. We have taken an extensive data set in the H2 test beam for pions and electrons and for no field and 3 T field strength and for 20, 30, 50, 100, 150 and 300 GeV beam energies.

The B field effect is a change in the HCAL response to the EM component of a hadronic shower. The e/γ energy is deposited in ECAL. The HCAL response to pions is:

$$E(B=0) = e*Fo + h*(1-Fo) \qquad (3)$$
$$E(B=4T) = e*Fo*(1+\delta) + h*(1-Fo)$$

The HCAL response to electrons is:

$$Ee(B=0) = e \qquad (4)$$
$$Ee(B=3T) = e*(1+\delta)$$

We use the electron beam to determine the increased response to the EM part, δ. It s understood in Eq.3 and Eq.4 that muons are used to normalize the energy responses in order that the scintillator brightening effect be removed. The data shown in the HCAL TDR indicate that, in the orientation of the scintillator package with the least sensitivity - scintillator toward the rear of the gap -, the factor δ is ~ 10%.

If e/h = 1, and if Fo = 1/2, then the effect on pion response is a 5% increase. We expect Fo to --> 1/3 at low energies and to --> 1 at asymptotic energies. For e/h = 1, the full variation in response is from a 3% increase at low energies to a 10% increase at very high energies. Note that this variation is small, correctable, and less than the residual nonlinearity shown in the TDR due to the e/h ratio being different from 1.

17. HE Optical Package:

A schematic of the HE tile – WLS package is shown in Fig. 12. The HE tile/WLS is packaged as a “megatile” at fixed radius. The HE “megatile” is packaged as a slice of azimuth at a fixed z location. The base materials are the same for HE and HB, although the detailed topology is slightly different in order to meet the requirements.

The performance of the HB and HE optics is very similar. The HE “megatiles” are organized at 10 degrees in azimuth while the HB are 5 or 10 degrees. The largest tile for HE was scanned as per our QC procedure and found to have a maximum nonuniformity of 6%. A scan with a Ru source across the tile and along the diagonal is shown in Fig. 13. The small nonuniformity is localized to the fiber region, which is small with respect to a hadronic shower size, and hence washed out, by the size of the probe. As shown in Fig. 6.6 of the HCAL TDR, this level of uniformity meets the HCAL requirements.

The scintillator is SCSN81 produced by Kuraray. Its narrow machined edges are covered with white reflective paint and the other sides are covered with Tyvek paper. The holes between the tiles are made to fix outside megatile covers. The uniformity of light collection for the largest tile is measured to be 6%. The space resolution measured with 22 cm x 22 cm tiles was 1.8 cm/$\sqrt{E}$ + 0.6cm. The decay times and the radiation resistance of HE and HB are discussed elsewhere in this document.

18. Magnet Trips:

Introduction

The discharge of the 4T solenoid in which HB resides will induce eddy currents in the conductive components of the modules. We estimate here the eddy current heating that will result in the inner and outer structural stainless steel cylinder of the barrel, which are bolted continuously along the barrel length, and in the copper of an individual module.

Approach

Any closed conductive path encircling changing flux will contain eddy currents. Because the hadron barrel consists of eighteen modules mechanically connected only at their inner and outer radius, there are two main areas of concern: The loops consisting of the inner and outer radius stainless steel plates, which connect to form cylinders approximately five meters in diameter, and the modules themselves, which contain several possibilities of smaller loops. The general approach will be presented first, then applied to the components.

Eddy current heating of thin cylinder in discharging solenoid

The voltage induced in a thin conducting cylinder enclosing within area A a uniform field B decaying at the rate dB/dt is

$$V = (dB/dt)\, A \qquad (5)$$

If

- σ = resistivity of cylinder material
- r_m = mean radius of cylinder
- t = thickness of cylinder
- L = length of cylinder
- R = total resistance to induced voltage

the current induced in the cylinder by the changing solenoid field is

$$I_e = V/R \qquad (6)$$

where

$$R = 2\pi r_m \sigma / tL \qquad (7)$$

Application to Hadron Barrel Stainless Steel Cylinders

From the CMS Magnet TDR, the maximum current decay is taken from Fig. 16.11 for the case of quench detection system failure, as 82 A/s. Assuming the rate of field decay to be proportional to the current decay, with 20 kA corresponding to a full field of 4T, then dB/dt = 0.0164 T/sec.

For the inner hadron barrel stainless steel cylinder,

σ = 0.704e-6 Ω-m
r_m = 1.84 m
L = 10 m
t = 0.07 m

Then, the area enclosed by the inner cylinder is A_i = 10.6 m^2. The induced voltage is V_i = 0.174 V. From the resistivity and cylinder geometry, R_i = 1.16e-5 Ω, and the total current in the inner cylinder is I_i = V_i/ R_i = 15 kA.

The joule heating is $Q = I_i^2 R_i$ = 2.6 kW. Assuming the decay rate to be constant from 20 kA to zero during the magnet discharge, the total time to discharge the magnet is 244 second, giving a total heat deposition of 634 kJ. If the specific heat of stainless steel is 0.46e3 J/kg-K, the density is 8000 kg/m^3, and the total volume of steel being heated is 8 m^3, then the temperature rise caused by the eddy currents (assuming no heat transfer to the surroundings) is 0.022 K.

For the outer hadron barrel stainless steel cylinder,

σ = 0.704e-6 Ω-m
r_m = 2.73 m
L = 10 m
t = 0.07 m

Then, A_o = 23.4 m^2, V_o = 0.38, R_o = 0.75e-5 Ω, and I_o = 49 kA. The joule heating is 18 kW, and the total heat deposition is 4400 kJ. The total volume of steel being heated is 12 m^3 with a total mass of 96000 kg. The temperature rise caused by the eddy currents
is 0.102 K.

Application to an Individual Module

The possible eddy current paths within a single module are very complex, and to simplify the analysis, the module will be assumed to consist of a cylinder with mean diameter equal to the largest module dimension, with a wall thickness equal to the thickness of a copper plate.

For this copper cylinder,

σ = 0.0156e-6 Ω-m
r_m = 0.81 m
L = 10 m
t = 0.061 m

The area contained by this cylinder is 2.06 m^2, and the resulting voltage is 0.034 volts. The resistance is 5.025e-7 Ω. This produces a current of 67.7 kA, and a joule heating of 2.3 kW, and a total heat deposition 562 kJ. If the specific heat of the copper is taken as 0.381e3 J/kg-K, the density 8954 kg/m^3, and the volume 0.31 m^3, then the total mass of copper is 2775 kg, and the resulting temperature rise is 0.53 K.

Conclusion

The eddy current heating of the hadron barrel calorimeter was calculated assuming a worst-case discharge rate, and found to be negligible for both the stainless steel and copper components.

19. FEA of HB and HE:

Shear forces in HB

The bolts do not take shear force. (For them to do so, the bolt shaft would have to be tight against the clearance hole in the unthreaded plate. In this case the bolt could not be inserted.) Rather, all shear is taken on the shear keys or shear pins. The details of how the shear key is engaged during assembly are described in Section 2.8.6 of the HCAL TDR. In addition, a large safety factor exists in the form of frictional forces between the copper plates. We have measured a coefficient of friction of 0.14 between the plates. This will allow the plates to withstand enormous shear forces (the preload is 10,000 lb./bolt) before slipping. These forces have not been used in assessing our factor of 2 safety goal.

FEA loading assumptions for HB and HE

The HB will be installed permanently inside the cryostat in the collision hall. This will be done in a very controlled, slow manner, taking of order a week. In contrast, the HE, installed on the endcap iron structure, will be moved (along with the endcap structure) during each access to the interior of CMS. Therefore the HE must be designed to accommodate these routine operations, while the HB does not.

HB FEA model allowing larger deformations

Initially we studied 2 variations of the wedge FEA model. In one model the bolted plate had a moment, and there was no penetration of the plates. The second model was one where the bolt was modeled as a point spot weld, with no moment, and the plates could inter-penetrate. The second model was found to have larger deformations AND larger internal forces. For this reason, the second model was chosen as a worst case estimator.

20. Radiation Damage to Scintillator:

As shown in the TDR, the best estimate for HB and HE of the radiation field indicates that the dose in HE is ~ 3 Mrad at $|\eta| = 3$. The dose due to minimum bias events falls off with increasing angle as $1/\theta^3$ or $\exp(3|\eta|)$. Thus the region where there is a large dose is very localized in a few towers of HE. We relate the dose to the damage roughly as an exponential with a characteristic dose as a parameterization of the induced color centers reducing the transmitted light output.

$$\text{Light Yield} = \exp(-D/Do) \qquad (8)$$

In the TDR we presented data on our baseline tile/WLS assembly. For comparison we show here the SDC data [6] in Fig. 14. This semilog plot illustrates the validity of Eq.8. Note that at a dose of 3 Mrad, the tile/WLS has lost 60% of its light output. We have chosen SCSN81 scintillator and BCF91A WLS because they combine machineability with reasonable radiation hardness. This baseline is justified in detail in the SDC TDR [1].

Note that for $|\eta| < 2$, the dose is < 0.4 Mrad. In that region, the damage is < 20%. As shown in the TDR the induced constant term with 2 HCAL compartments is ~ 4% for a 50% light loss and the functional dependence is roughly linear. Thus, for the $|\eta| < 2$ region, we have a 1.6% induced constant term folded in quadrature with the undamaged 5% HCAL constant term. Therefore, the baseline is to maintain only 2 hadronic compartments in the wide-angle region.

For the $2 < |\eta| < 3$ region the dose is < 3 Mrad, indicating a damage < 60% light loss. As shown in the TDR, the 2 compartment light loss would induce a ~ 7 % constant term. To alleviate the loss of energy resolution, we adopt a third longitudinal compartment of depth ~ 2 λ directly behind H1. The 3 compartment HCAL has a ~ 1% induced constant term for 60% loss of light.

In addition, the radiation field has some error, and therefore it is prudent to have some additional handles on the radiation damage. To that end we added yet another compartment in the small angle region of HE and also extended the angular range where there is 3-compartment coverage. These give us added protection. Finally, during long annual shutdowns, one can use the radioactive source to map out the damage profile and then use photographic “masking” at the HPD “cookie” to make the HE longitudinal profile uniform again. The technique loses light, but as the physics resides largely in Et, the loss of physics capability is small.

If all else fails, or if there is a catastrophic beam loss or accident, the HE scintillator sectors are thought to be constructed with a replaceable inner small angle segment. These could be replaced during a long access shutdown, but this is not thought to ever be needed during normal operation of CMS.

21. Pileup Noise in Higgs Searches:

There was an initial study of Z → JJ for low and high Pt Z bosons [10]. The pileup clearly adversely effects the Z mass resolution, see Fig. 15. In addition, we have studied pileup noise for H → ZZ → llνν and for H → WW → lνJJ. [11]. For the ZZ case, the missing Et cuts depended sensitively on the pileup, necessitating a tower Et cut before the global Et was computed. For the WW case, the usefulness of the cuts is reduced by pileup. This being the case, CMS HCAL is designed to be fast. The tile/WLS time constants were measured to be < 12 nsec [6]. These are well matched to the LHC bunch crossing time of 25 nsec. The HPD will be required to not degrade the intrinsic speed of the tile/WLS active sampling.

Yes, pileup makes things worse, but the resolution degradation is an unavoidable physics effect. We have chosen the fastest available calorimeter technology to minimize the effect. H → bb is likely to be a low-luminosity physics topic, both in the associated production mode and in the cascade decays of SUSY particles. In both cases cross sections are high, and there is a premium on the best b-tagging being available, so it would be done at a luminosity of 10^{33} $cm^{-2}sec^{-1}$ with negligible pileup.

22. Dijet Mass Distribution and Pileup:

This process has been studied. [10,11]. The fractional mass resolution of a Z -> JJ is shown in Fig. 15 with and without pileup as a function of cone size. For 1 bunch pileup at full luminosity the degradation of resolution is already noticeable. Therefore, there is a premium on keeping the sensitive time of HCAL as short as possible.

As regards long time constants in the system, we show tests of the timing of the system. In Fig. 16 the top trace is for direct LED illumination of an HPD. The pulse has ~ 20 nsec FWHM, when operated at 180 V bias, which is an approximation to the next HPD version with 150 μm Si thickness. The bottom trace is for LED illumination of a tile/WLS + optical fiber + HPD combination representing the behavior of the CMS HCAL. The FWHM is ~ 30 nsec, which illustrates that the HPD time constants are well matched to the scintillator deflourescence times. We have checked that assertion by taking timing data with fast PMT (Hamamatsu R647-17) instead of the HPD. In this case the FWHM is ~ 20 nsec, which indicates the intrinsic time resolution of a tile of finite size and a WLS.

Clearly, there are no long time constants in the CMS HCAL system.

23. Muon Signal and Timing:

A single exponential fit to the time response of the scintillator-waveshifter combination gives 11.3 nsec (HCAL TDR, page 405) or 8.2 nsec as measured in SDC tile\WLS [6]. There are differences due to the WLS differing from Y11 (CMS) to BCF91A (SDC). Our simulations of the time structure include the impulse response of the HPD and a rectangular distribution for the loop length effect. The result is, on average, 68% of the signal occurs in the event crossing itself, 29% occurs in the subsequent 25 nsec interval, and 3% occurs in the interval following that. At 10 photoelectrons average, the three samples yield 6.8, 2.9, and 0.3 photoelectron signals. There are significant Poisson fluctuations on these average values. We have tested the time slew in the lab at the 10 p.e. light level using a tile/WLS coupled to a DEP HPD and we find a time slew of the leading edge of 4-6 nsec.

The efficiency of a simple sliding, three-sample sum algorithm is very high in the absence of pileup from adjacent crossings. Simulation of the efficiency as a function of luminosity is work in progress. At the present level of understanding, the occupancy in the tailcatcher compartments (HOB and HOE) is well below 1%, closer to 0.1% because of the depth in the absorber. Therefore, the spread in arrival time of the muon signal is not critical for the muon detection efficiency.

24. Sensitivity of the Fibers to Showers:

The fibers in question are clear, so that the signals induced by showers would be due to Cerenkov emission. This effect is thought to be small. A similar device, the CDF endplug calorimeter, had the fiber readout scanned by the test beam, with no discernable effect. We plan to scan the crack region in the H2 test bean to look for both “hot” and “cold” spots in the calorimetry in our 1998 test beam runs.

25. Electronics Packaging:

For the roughly 9000 channels in the barrel (HB) and end cap (HE) readout boxes, the packaging is determined by the locations, small pockets carved out of the absorber as indicated in Figure 9.1 of the HCAL TDR. The smallest possible footprint is necessary to minimize the effect of lost material on calorimeter performance. In addition, the digitized results from three channels are multiplexed onto one fiber readout link. Thus, the natural grouping of channels is by threes, 3, 6, and 9, channels per group. A three-channel printed circuit card unit was the optimum in terms of space utilization in HB as all of the readout cards are accommodated in the space between the two columns of fibers from the calorimeter layers. Using 6 or 9 channel cards makes the box longer in the z-dimension. The three-channel card also works well for HE making for a compact design there as well. There are a total of 60 readout boxes in HB and HE.

The tail catcher compartments in the barrel (HOB) comprise about 2200 channels, but require 60 separate readout stations to keep the readout fibers to a practical length. On average, there are only 36 channels per readout station. This makes a crate solution completely impractical, and the choice made was to use the same technology in HOB as developed for HB and HE. Everything is the same except the width of the box is smaller as appropriate to the smaller number of HPDs. A side benefit is the high reliability that comes from meeting HB and HE requirements.

The forward calorimeters are compact objects with open access to the sides. A crate-based system was chosen and there are four 9U VME64 crates planned per end to house the cards. Because the noise floor and ADC granularity requirements are quite challenging, it was decided not to solve the problem twice, once for the readout box three-channel cards and once for a 9U by 400 mm card. Instead, the three-channel cards will be converted to mezzanine cards on a 9U carrier board for a total of 33 channels per VME card.

The estimate for VME crates on page 503 of the HCAL TDR refers to the digital electronics located in the underground equipment room adjacent to the detector cavern, not to the front-end electronics discussed above. This estimate is in conflict with the one made on page 483 in the Trigger and Data Acquisition Electronics chapter, and it is an undetected failure to update all instances of the VME crate count estimate in the TDR. Please consider the number on page 503 as an outdated (and uncorrected) estimate.

26. HF Noise Floor Requirements:

The HF noise floor discussion on page 408 does indeed neglect the contribution from the photomultiplier tube gain dispersion. It assumes that the width of the single photoelectron signal is entirely due to the electronics noise, basically that the tube behaves like an HPD. This is clearly not correct, and the true situation is the exact opposite. The width of the single photoelectron signal is determined by phototube gain dispersion not by electronics noise.

In the test beam situation, under good conditions, the pedestal distribution had a sigma corresponding to 8% - 12% of a photoelectron. This parameter was reasonably well measured as the settings used produced a calibration of 5 ADC counts per photoelectron. Under these conditions, the single photoelectron peak was cleanly separated from the pedestal resulting in high efficiency and an acceptable signal-to-noise figure. Therefore, a noise floor of 10% of a photoelectron should enable HF to achieve test-beam quality performance. (The referee has suggested a noise floor of about 6% of a photoelectron, which is quite consistent with the test beam results).

Assuming that the noise floor requirement for the HPD readouts, 3000 electrons rms, is achieved, the HF phototube gain needed for a 10% photoelectron noise floor is $3*10^4$. In order to avoid replacing the phototubes at the highest $|\eta|$ positions, the gain should be limited to about $4*10^4$, so the correct noise floor requirement for HF is very similar to the HB and HE requirement.

27. Minimum HPD Gain Requirement:

The working number of 2000 for HPD gain was chosen as a conservative value to deliberately confront, in the TDR, issues of noise, source current readout, and ADC granularity. In addition, the high voltage required for this gain is less than 10 kV. All devices fabricated so far easily operate at gain 2500 and higher. The vendor has advised that operation at gain 3000, about 12 kV, would pose no problems based on their long experience with the night vision parent device. Our strategy was not to execute the TDR based on gain 3000 and discuss separately the consequences of only achieving gain 2000, but to design for gain 2000 and use operation at gain 3000 as our contingency against falling short on the noise floor figure.

28. Ground and Cooling:

A single point ground architecture is planned with that point located at the readout box to minimize EMI problems. The cooling system uses flexible 3/8 inch diameter “power supply” reinforced hoses, a separate supply and return pair for each readout box. This choice was made because of cost; it avoids the expensive pipefitting that comes with using rigid metal lines. However, it also avoids any ground loop problems from the cooling system as the hoses are fabricated from synthetic rubber.

The electronics is packaged as board doublets laminated to both sides of a copper plate. This lamination is done using thermally conductive but electrically insulating material. Therefore, all of the electronics is electrically isolated from the cooling system. We may provide the capability of making a single point ground connection between the two systems just in case we want them connected. As designed, the cooling system can be grounded without grounding the electronics.

29. Impact of the Source on Front End Electronics:

We have only a single data path for HCAL. We exploit the fact that we have a long pipeline in order to create a quasi D.C. measurement of the source current using the same data path as used in the main data taking.

The source calibration system uses extreme over-sampling and has no effect on the design of the front-end electronics. In order to implement this calibration technique, it is required that the trigger and DAQ system be able to take a few 10,000s of events as the source moves across the detector and be able to average the data from these events to a reasonable precision. Since the calibration will occur off-line (not during data taking), the main impact is on the trigger system which has to provide a source of triggers to the front-ends so they will pass the data along. The processing of the data can be done anywhere in the computing farm system, which should have more than enough capacity for the task.

Radioactive source data is taken using the normal 40 MHz data recording scheme. The pipeline is simply filled with samples of the source the sum of which constitutes a D.C. measurement. A histogram is accumulated for each data point, which is then fit to a Poisson distribution, convoluted with the Gaussian noise shape. The calibration consists of determining the mean number of photoelectrons per 25 nsec interval. Further discussion can be found on pages 425 and 443 of the HCAL TDR and below. Normal trigger services are used, but in-crate processors are needed to accumulate and fit the histograms. These processors are planned to be the normal Detector Control System in-crate processors as this resource is idle during such calibration. Extra electronics are not required but additional functionality is needed in the Front End Drivers to provide a data path from the trigger and DAQ electronics to the controls processor.

The problem of making an absolute calibration using a radioactive source is that the current from the HPDs during source calibration is very small compared to the signal level during normal operation. One method considered was to include a switch on the front end of each channel and 2 read out paths, one for normal operation and one for calibration. This was rejected due to its adding complexity and reduced reliability. A second option was to slow down the clocks to the front ends so that they would integrate over a longer time window. While this does not add to the component count in the front ends, it does impose a condition on the QIE that it be able to operate with 2 very different bias currents. (The bias current is injected into the front end of the QIE to make it linear and to assure that it has a positive pedestal.) The QIE is easier to design if it only has a single bias current. We therefore adopted a third method for source calibration. The third option is to run the system in its normal mode at its normal clock speed and to measure the small source currents by extreme over sampling.

The current from the source is used for calibration of the HCAL tiles. It is possible to measure this current to a few tenths of a percent of an LSB using the noise in the system by averaging over a large number of readings. This only requires that the electronic noise width of the pedestal be ~ 1, and that the electronic noise be Gaussian. The source current will be limited by the photo-statistics in a 25 nsec sample and will thus have a Poisson distribution. Since the pedestal reading is an integer representation of the input current summed with the pedestal, the noise will cause the pedestal to "flicker" about the standard pedestal value. Any additional current will cause this pedestal flicker to be offset and will result in a new average pedestal value, the source current is then measured by doing the subtraction of "Source in Pedestal" - "Source out Pedestal". These pedestals must, of course, be measured very precisely by measuring the integer pedestal many times and calculating an average.

The one caveat is that the noise must be random in relation to the sampling window. The Poisson component of the signal acts as a noise source on its own with a width of more than 1 LSB

Simulation

A simple Monte Carlo program was written which has a fixed "source out pedestal" of X Counts and a variable Gaussian electronic noise width for this pedestal. The program measures this pedestal using 100,000 samples and then "injects" a small fixed mean, Poisson distribution charge into the pedestal on top of the noise and makes more measurements of the new "source in pedestal" and then subtracts the 2 and reports the measured source current. Even for a very wide electronic pedestal of 0.8 counts (the KTeV system measures 0.3 LSBs) the program finds the source current to 1% in about 5,000 samples and to 0.5 % LSB in about 100,000 samples. While this is a large number of samples, the data rate for this calibration is below the normal data rate for the experiment when it is running.

As can be seen from the example simulation run shown below, the injected currents can be measured quite accurately using the noise of the signal itself and extreme over sampling.

Target Ped = 10.7, Electronic Ped Width = 0.8, source current mean value = 5.9. Measured Ped = 10.70207

Samples	Ped	Current	Error	% Error
10	16.700000	5.997930	0.097930	1.659831
20	16.450000	5.747930	-0.152070	-2.577458
50	16.340000	5.637930	-0.262070	-4.441864
100	16.770000	6.067930	0.167930	2.846271
200	16.515000	5.812930	-0.087070	-1.475763
500	16.622000	5.919930	0.019930	0.337797
1000	16.732000	6.029930	0.129930	2.202203
2000	16.516000	5.813930	-0.086070	-1.458814
5000	16.613800	5.911730	0.011730	0.198814
10000	16.598200	5.896130	-0.003870	-0.065593
20000	16.607050	5.904980	0.004980	0.084407
50000	16.616820	5.914750	0.014750	0.250000
100000	16.602220	5.900150	0.000150	0.002542

30. The Advantages of a CW Base for HF:

We appreciate the committee's query about possible lower cost solutions to the HV for the PMT used in HF. We believe that there is sufficient time and design flexibility in the PMT boxes and the HF HV system and electronics racks that a lowest cost solution with minimally acceptable performance can be found in a timely manner.

We recall:

(a) ~50-100 μA of pulsed signal is the average current from the high |η| towers - more if the gain needs to be increased. A purely resistive base would need a power supply of >10 mA (i.e. >100x average current) to maintain a linearity of +/- 2%.

(b) The pulse risetime is ~2 nsec with the charge at the photocathode developed in <4 nsec from the Cerenkov light.

(c) The rate in the HF calorimeter towers will be as much as 40 MHz, or higher at the 1-3 p.e. level (neutrons, photons); the corresponding duty factor (DF) may be as high as about 5 nsec pulsewidth/25 nsec crossing or up to 25% for the pmt.

The basic "base" options are:

(1) Booster supplies: can be used to increase the linearity of a resistive PMT base- we have demonstrated that in test beams up to ~350 GeV (XP2020) But these tests were done a low instantaneous rates (i.e. not at 40 MHz) A single booster supply voltage base still requires a substantial current drawn from the prime supply - If one supply is used on all but the last 2-3 dynodes, it still must supply ~ 1/10 of the base current. To achieve 2% linearity, one must have >100x the average current or 100 x 10 μA = 1 mA. The other supply must still supply ~10 mA, albeit at a much lower voltage. It is not clear that cost savings will result, as there will still need to be large resistors and power drop on the base, on both parts of the chain. In general, with a resistive base, even boosted, one pays for ~100 times the HV power actually used. These bases operate at 40 MHz; it is not clear that the time constants needed to recharge capacitors used at a >10% duty cycle are reasonable. In the literature, boosted bases sag beyond 100 kHz, and are the raison-d'être for transistorized bases; certainly bench tests by us show little hope of linear

operation beyond 1 MHz of rate (even though at lower rep rates linearity of nearly 10^4 can be obtained).

(2) Transistorized bases: use active switching on the last dynodes to maintain the dynode voltage only during current draw. Our contention is that these bases will be switched as often as every beam crossing (i.e. at 40 MHz), and so this become less effective than in the normal situation where a peak rate in a calorimeter is < ~1 MHz (note also that some parasitic power is consumed in the switching). The aggregate rate may be higher considering the noise levels from neutrons or other backgrounds

In this situation, one pays for relatively high speed/HV transistors (i.e. rated at >200 V for reliability). We are operating a system with a duty factor ~ few nsec/25nsec ~ 10-20%, and it is not even clear that capacitors on the transistorized chain will have sufficient time to recharge between pulses i.e. the transistors are basically left on, and the benefit of reducing power in the chain AND, more importantly, allowing the capacitors to recharge to the full voltage level, is essentially lost

It is not clear whether the active components in a transistorized base (note: a diode is normally also needed for each stage) would be the right choice in the HF radiation environment. (Note that it is not practical to operate these bases remotely from the tube - unlike the situation below).

(3) Cockcroft-Walton: These bases are highly efficient and need to provide only slightly more power than the pulsed anode current x HVmax. The references in the TDR attest to their properties for maintaining linearity, as have our bench tests. With sufficient capacitance, they are much more immune from rate effects not intrinsic to the tube (i.e. - they largely behave as if they are individual HV supplies on each dynode).

The cost of these (bases+HV) should be relatively comparable to a single controlled HV supply for any other PMT base (not including the base). Why? Typical PMT HV supplies often use a very similar circuit, perhaps with a few less stages of multiplication but higher voltage per stage, to reach 1-2 kV (i.e. similar to a HV series regulator circuit). For example, a LeCroy multichannel HV card uses 4 stages of capacitive/diode multiplier in its series regulator to reach 2 kV on each of the HV outputs on the HV card. Since a typical HV supply for a resistive base must create ~mA, and we need ~0.1 mA for a C-W base, it is quite reasonable to assume that the few extra diodes and capacitors (and LOWER turns ratio/HV transformer) needed for a C-W base results in a "tapped HV supply" (i.e. a C-W base) cost that is quite comparable to the cost for a single channel of controlled HV needed to power a resistive-type or transistorized 40 MHz base (not including the transistorized base itself). The control circuitry needed for the C-W base is essentially identical to that needed for each individual HV supply needed for any other base.

A C-W base including control circuitry on the base is likely to be the least rad-hard base. However, the C-W "base" also enables a design, which allows the fewest active or passive components on the base. We anticipate choosing a C-W base with the C-W circuit separated from the PMT by multiconductor cable. The "base" at the PMT thus consists only of a PMT socket, a multipin connector for the dynodes and cathode HV, some local charge buffer capacitors on the last 4-5 stages (i.e. no appreciable RC time constant, only a local store at the end of the dynode cable), and a signal connector (and a signal matching network or preamp if necessary). The "bases" are then built as HV cards in a manner similar to existing HV cards for single supply bases, but with a more complex connector.

Summary: The HCAL group will make no final HV plans until prototype HV systems are properly costed, either via commercial bids or as documented in an engineering design report on the various base options, including the cabling and the HV power supplies needed for operation. Our choice in the HCAL TDR was dictated by the extreme demands placed on the HV and PMT by the 40 MHz rates.

Moreover, no mechanical nor electrical designs will be frozen in the near future that precludes one HV design over another (for example the PMT boxes will be designed to accommodate any of the base choices without difficulty).

31. The HV Fanout and HB/HE Risk:

One high voltage supply serves all HPDs in a given readout box. This supply is located in the underground service room adjacent to the detector cavern where it is accessible at all times. To protect against coupled failures taking out a large number of channels, separate high voltage leads are brought in for each individual HPD in a box. Should high voltage problems arise, the HPD in question can be removed from the “bulk” supply and put on a separate individual supply or left off in the worst case.

32. Cooling and Heat Load, Leak Risks:

We originally designed the cooling system to handle 500 watts, the current best estimate is less than 300 watts. Even at 500 watts we had at least a 50% margin in terms of cooling headroom. Unless the power consumption in the crate goes up by more than a factor of 2, we have no problem, and even a factor of 3 could easily be handled by increasing the flow rate and/or the ΔT of the water.

The power dissipation engineering estimate is on the high side for several reasons. The QIE power consumption is based on 2 micron technology while an 0.8 micron BiCMOS process is envisioned. The ADC is a catalog item, but the most likely outcome is that the ADC is brought on-board the digital control ASIC eliminating the high power of driver/receiver circuits. The optical links power budget was taken at the level of today’s commercial technology, not at the anticipated level of such technology in 4 year’s time.

Cooling hoses were sized based on these power consumption estimates and only moderate operating pressures. The rating of the hose is such that the flow can be increased by a factor of 4 by going to full design pressure. This feature is not a design outcome, rather it is due to sticking to commercial catalog hoses and avoiding a custom product. The next size smaller hose would be operating at about 70% of capacity if the heat load turned out to be as high as the escalated estimate in the TDR.

Coolant leaks anywhere in the detector could have major consequences; there are electronic systems and high voltages more or less everywhere. Cooling systems more than an order of magnitude larger than those for HCAL provide for the ECAL and the Tracker. The CMS integration group does not favor the “leakless” cooling system for two reasons, cost and past experience. Costs are high because gravity limits the vertical extent of the system to less than 10 meters, probably about 8 meters in practice, so that many systems at many different elevations are needed. Their past experience in L3 has been mostly bad.

The connections to the decoder boxes are NOT quick connects but are permanent connections of a type which have historically been proven to be of high reliability. Further, the pressures needed for the cooling loops are less than 5% of the working rated pressures of the lines and are less than 1% of the rated burst pressures of the lines. We believe that with adequate quality control during assembly and by pressure testing the system first using a gas, the system will provide reliable leak-free operation.

The preferred mitigations are in the area of prevention. High quality installations, which adhere to a piping code, permit a quantitative failure mode analysis as the failure rate per operating year is known. It is possible to design for an acceptable failure rate over 10 years. Operating at reduced pressures as is the case for HCAL also reduces the failure probability by reducing stress and erosion at bends or elbows, but a hard quantitative evaluation of the improvement factor is not available. Finally, there is the human factor, and discussions have begun about protecting the cooling lines from induced external damage.

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Figure Captions:

Figure 1: Dijet mass resolution for H → bb for a 100 GeV mass Higgs. The plots are for HCAL energy resolutions which span the baseline TDR design. The effect of calorimeter resolution is minimal.

Figure 2: Dijet mass resolution as a function of HCAL transverse segmentation. The circled Monte Carlo is for W → JJ with W at rest, while the points are for boosted W with Pt = 0.5 TeV.

Figure 3: Dijet mass resolution for Z and Z' (1 TeV) for low Pt and for high Pt. The conditions a-g are defined in the body of the text.

Figure. 4: Dijet cm angular distributions for different HCAL tower transverse segmentation.

Figure 5: Scatter plot showing the correlation of the H1 compartment energy with the remainder of the CMS calorimeter energy.

Figure 6a: Fractional energy resolution for 300 GeV pion beam for 1 and 3 layer H1 compartment as a function of the constant weight applied to the H1 readout.

Figure 6b: Mean energy for a 300 GeV pion beam for 1 and 3 layer H1 compartment as a function of the constant weight applied to the H1 readout.

Figure. 7: Scatter plot of energy inside the solenoid vs. the energy outside the solenoid in the HO layers for single 300 GeV pions.

Figure 8: Field map for the CMS Magnet as a function of (r,z).

Figure 9. Data on tile/WLS timing read out by a PMT.

Figure 10: Schematic of the HF PMT box, where the magnetic shielding is indicated.

Figure. 11: Data on scintillator response to magnetic fields at fields up to 10T. There are source illuminated and e beam illuminated data for comparison.

Figure 12: A schematic of the HE tile + WLS arrangement. The arrangement is very similar to that for the HB optics. The base materials are the same.

Figure 13: A plot of the response of a HE tile to a collimated Ru source moving entirely across the tile. The top plot is a scan across the centerline, while the bottom plot is a scan along the diagonal. A small effect is seen to be localized to near the fiber location.

Figure. 14: The fractional light loss for several test modules in SDC as a function of dose in Mrad. The exponential behavior is evident.

Figure 15: The fractional mass resolution for Z $\rightarrow$ JJ as a function of jet cone size for low Pt Z bosons. The effects of pileup are shown; with and without a tower Et cut.

Figure 16: The time spectrum for an LED exposure of the CMS HCAL. The top trace is for the HPD by itself, run at 8 kV cathode potential and 190 V bias potential. The bottom trace is for illumination of a tile/WLS + optical cable + HPD.